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# Stellar Accretion and X-Ray Emission

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The blue stellar object which has been identified with the strong Scorpius x-ray source[1] emits about $10^3$ as much energy in the x-ray region as in the visible region. In a previous note[2] one of us suggested that the vibrations of a compact star with a massive electron degenerate core might be able to shock-heat a surrounding coronal region which could have these properties. This idea has been tested through a variety of hydrodynamic model calculations[3]. It has been found that even with overoptimistic assumptions about the parameters, the resulting x-ray emission falls at least two orders of magnitude short of the $4 \times 10^{36}$ erg/sec. which appears to characterize the Scorpius source.

Meanwhile, Shklovsky[4] has suggested that the Scorpius x-ray source is a member of a close binary pair of stars. He proposed that one of the stars is a neutron star and that it is rapidly accreting mass from its companion. The release of gravitational potential energy then creates hot plasma which radiates thin-source bremsstrahlung in the x-ray region.

In this note we consider some general properites of mass accretion onto a compact star. We then point out some difficulties with Shklovsky's suggestion and suggest an alternative model.

It should first be noted that there is an upper limit to the rate at which mass can accrete onto a star, which results when the outgoing radiation stress on the infalling material becomes equal to the gravitational stress. This condition is

$$\frac{N_o}{\mu_e}\frac{\sigma_T}{c}\frac{L}{4\pi R^2} = \frac{GM}{R^2}$$

where $\sigma_T$ is the Thomson scattering cross section, L is the luminosity generated by the infalling material, $N_o$ is Avogadro's number, and $\mu_e$ is the mean mass per electron. For a star of one solar mass, with $\mu_e = 4/3$, the resulting maximum luminosity is $1.7 \times 10^{38}$ erg/sec., which is considerably larger than needed to account for the luminosities of x-ray sources. For reasons which will emerge below, we take the total luminosity of the Scorpius source to be at least four times the apparent x-ray luminosity, or about $1.6 \times 10^{37}$ erg/sec.

In the following discussion the following pattern of events will be investigated. The infalling material is optically thin and the time required to cool by radiation is long compared to the infall time. When the infall is halted the released gravitational potential energy is converted to gas kinetic energy; the plasma remains optically thin. The temperature characteristic of the resulting thin source bremsstrahlung is estimated. The absorption and reemission of radiation by the underlying stellar surface is also considered.

When the infalling material is halted, the released gravitational potential energy is converted into gas kinetic energy. The maximum (coronal temperature which thus results is

$$T_c = \frac{2}{3} \frac{GM\mu}{N_o kR} \tag{2}$$

where $\mu$ is the mean molecular weight, G is the gravitational constant, M is the stellar mass, and we have assumed that the conversion takes place at the stellar radius R. For a star of one solar mass, with

$\mu = 2/3$,

$$T_c = \frac{7\text{x}10^{17}}{R}$$

For a neutron star $R \approx 10^6$ cm., and $T_c \approx 7\text{x}10^{11}$ $^oK$. This high temperature indicates that the gas contains relativistic electrons, but corrections for relativistic effects need not be made at the present crude level of our considerations. For a white dwarf we take $R \approx 2\text{x}10^8$ cm., and hence $T_c \approx 3\text{x}10^9$ $^oK$.

It is also possible to estimate the pressure at the coronal level where these high temperatures are produced. The rate of momentum transport for freely-falling material will be equal to this pressure. The free-fall velocity is

$$v_f = \left(\frac{2GM}{R}\right)^{\frac{1}{2}} \tag{3}$$

The mass flux necessary to produce the total stellar luminosity is

$$\rho v = \frac{R}{GM} \frac{L}{4\pi R^2} \tag{4}$$

Hence

$$\rho_f v_f^{\ 2} = \frac{N_o}{\mu} kT_c \rho_c \tag{5}$$

from which we find

$$\rho_c = \frac{3L}{2^{5/2}\pi G^{3/2} M^{3/2} R^{1/2}} \tag{6}$$

The coronal scale height in this region is

$$H_c = \frac{N_o kT_c R^2}{GM\mu} \tag{7}$$

Hence for one solar mass the amount of material overlying this point in the corona is

$$\rho_c H_c = 1.17 \times 10^{-3}\ R^{\frac{1}{2}}$$

For a neutron star $\rho_c H_c = 1.17$ gm./cm.$^2$. For the gamma-rays which will be radiated in this case, the effective cross section is less than the Thomson cross section. Thus the optical depth is not too large and the incoming material can radiate without much absorption. However, for a white dwarf $\rho_c H_c = 16.5$ gm./cm.$^2$, which indicates that the above crude picture is not quite correct; the infalling material will stop close to the photosphere. It is necessary to determine where the radiation will occur in this case.

Of course, the infalling material is not stopped completely, since the incoming mass flux must be constant. Let us consider the fractional energy radiation $\Delta E/E$ of the material as it moves through a coronal scale height with the properties estimated above. The rate of energy radiation by thin-source bremsstrahlung[5] is $\sim 2 \times 10^{-27}\ T^{\frac{1}{2}}\ n_e n_i$ erg/cm.$^3$sec., where $n_e$ and $n_i$ are the number densities of electrons and ions. We write the energy loss rate as $2 \times 10^{-27}\ T^{\frac{1}{2}}\ N_o^{\,2} \rho / 4\mu^2$ erg/gm.sec. The time required to move through a scale height is $H_c/v$, and the energy available for radiation is $E = GM/R$ per gram. Hence

$$\frac{\Delta E}{E} = 2 \times 10^{-27}\ \frac{T_c^{\frac{1}{2}}\ N_o^{\,2} \rho_c}{4\mu^2}\ \frac{H_c}{v}\ \frac{R}{GM} \qquad (8)$$

From (2), (4), (6), and (7) we have

$$\frac{\Delta E}{\Delta} = \frac{3^{\frac{1}{2}}\times10^{-27}}{2^{5/2}\pi}\;\frac{N_o^{\;3/2} L R^{3/2}}{k^{\frac{1}{2}} G^{5/2} M^{5/2} \mu^{3/2}} \tag{9}$$

For one solar mass this becomes

$$\frac{\Delta E}{E} = 5.5\times10^{-13} R^{3/2}$$

For a neutron star this is $5.5\times10^{-4}$, showing that negligible radiation occurs before the infalling material is slowed and attains its high temperature. For a white dwarf star $\Delta E/E \approx 1.5$. This appears to indicate that the gas energy will be radiated away as the material slows down, but it must be remembered that a full scale height of gas is optically thick, and the value of $\Delta E/E$ by the time the material has penetrated to a depth of $\sim$ 1 gm.cm.$^2$ is $\sim 1.5/16.5 \approx 0.09$. Hence in this case also the material arrives in the vicinity of the photosphere with most of its energy intact.

If all of the released energy were to be radiated as blackbody radiation from the photosphere, the photospheric temperature would be

$$T_e = \left[\frac{L}{4\pi\sigma R^2}\right]^{\frac{1}{4}} \tag{10}$$

With $L = 1.6\times10^{37}$ erg/sec.,

$$T_e = \frac{1.22\times10^{10}}{R^{\frac{1}{2}}}$$

For a neutron star the photospheric temperature will be $\sim 1.2\times10^{7}$ $^{o}$K, and for a white dwarf it will be $\sim 8.6\times10^{5}$ $^{o}$K. These temperatures are very much lower than the coronal temperatures. Hence it is evident that a steep temperature gradient must be set up near the photosphere.

We must consider thermal conduction of energy in the presence of such a temperature gradient. The conducted energy flux is $\lambda dT/dz$, where $\lambda$ is the coefficient of thermal conductivity and z is the vertical distance in the atmosphere. For an ionized gas we may take[6]

$$\lambda = 5\times10^{-7}\ T^{5/2}\ \text{erg/cm.sec.}\ {}^{\circ}\text{K}$$

For the purpose of a crude estimate let us write for the ratio of the energy conducted out of the photospheric scale height, during the time of passage of material through the scale height, to the energy content of the scale height as

$$\frac{1}{EH_c\rho_c}\,\lambda\,\frac{T_c}{H_c}\,\frac{H_c}{v} = 3\pi\times10^{-6}\left(\frac{2}{3}\,\frac{GM\mu}{N_o k}\right)^{7/2}\frac{1}{R^{5/2}L} \qquad (11)$$

For one solar mass this is $1.8\times10^{20}/R^{5/2}$. For a neutron star the result is $1.8\times10^{5}$, indicating that conduction can most easily remove the thermal content of the gas during its motion toward the photosphere. This conclusion would not be altered if a proper relativistic treatment had been used. For a white dwarf star the ratio is 0.32. However, for this case a better estimate would be $0.32\times16.5 = 5.3$, and again conduction can remove much of the thermal content of the gas during its motion toward the photosphere.

In the case of the neutron star it is evident that a very small temperature gradient is sufficient to conduct away the energy flux from the coronal region. Hence the temperature gradient will not become steep until very near the photosphere. In both kinds of star the steep part of the temperature gradient thus occurs within a photospheric pressure scale height and both temperature and density will change rapidly at almost constant pressure.

It is further evident that the conductive transport of energy will no longer be able to exceed the mass transport when the temperature is lower, since the thermal conductivity varies as a fairly high power of the temperature. We may roughly estimate that the two transport rates are equal at the radiation temperature of the gas, and hence this radiation temperature will be the coronal temperature reduced by the expression in equation (11) raised to the power 2/7. Hence in the above example the neutron star would radiate thin-source bremsstrahlung at a temperature near $2\times10^{10}$ $^{\circ}$K, and the white dwarf would radiate at a temperature near $2\times10^{9}$ $^{\circ}$K.

It is evident that we do not find support in these results for Shklovsky's suggestion that the Scorpius x-ray source results from mass accretion onto a neutron star. For neutron stars the radius is a rather insensitive function of the mass[7], and hence any reasonable adjustment of the parameters in the expressions given above will not significantly lower the temperature at which the infalling material will radiate. Mass accretion onto neutron stars should give combination x-ray and gamma-ray sources. The x-radiation results from the absorption of the thin-source bremsstrahlung by the photosphere and its reradiation in a blackbody spectrum. Half of the stellar luminosity will arise from this process, so that equation (10) should be modified to become

$$T_e = \left[\frac{L}{8\pi\sigma R^2}\right]^{\frac{1}{4}} \qquad (12)$$

Thus the blackbody spectrum of a neutron star in our example should have a temperature of $10^7$ °K.

It is also evident that we have a much better chance of fitting the parameters of the Scorpius source if we assume a model with mass accretion onto a white dwarf. The masses and radii of white dwarfs are inversely correlated, and hence a much wider variation in parameters is possible. Since in our previous example the radiation temperature has come out too high, we must choose a lower mass which will have a larger radius. It is immediately evident from equation (11) that the conductive transport of energy will then become much less efficient, and the star will radiate at more nearly its coronal temperature. From the tabulated models of white dwarf stars[8], it can readily be found that a white dwarf with a mass near 0.2 solar masses will have a coronal temperature near $10^8$ °K. Its radius will be about $1.4\times10^9$ cm. For this case the upper limit on the luminosity from the radiation stress condition is $3\times10^{37}$ erg/sec., which is somewhat higher than the apparent Scorpius luminosity. The total rate of mass infall needed to produce this luminosity is about one solar mass per $10^5$ years.

These numbers are suggestive of the results obtained for the evolution of a close binary pair of stars by Kippenhahn, Weigert, and Kohl[9,10]. In their model the stellar primary transfers mass to the secondary after reaching the red giant phase; the transfer time is less than $10^5$ years. The remnant settles down as a white dwarf star of 0.26 solar masses; it has a hydrogen-rich envelope and hence a somewhat larger radius than a pure helium white dwarf. If such an object exists in the Scorpius x-ray source system, we would therefore lower the estimate of coronal temperature somewhat. Of course, we would see the system at a later stage than indicated by the final models of Kippenhahn and Weigert, when the secondary had also evolved to the red giant stage and is transferring mass back to the original primary.

For M = 0.2 solar masses and $T_e = 10^8$ $^{o}$K, the ratio of coronal pressure to photospheric pressure would be increased over the previous estimate by a factor $\sim$ 30. From equation (9) we see that $\Delta E/E$ would be increased by a factor $\sim 10^3$, so that the infalling material will radiate thin-source bremsstrahlung before the bulk kinetic energy has been fully converted to thermal energy. From these results it is evident that an effective photosphere will develope in the infalling material, and hence conductive effects will not be important. The estimate for the coronal temperature is too high also for this reason. A steep temperature gradient will be set up near the effective photosphere. As the velocity of the infalling material will rapidly decrease along this temperature gradient according to the continuity equation (4), the bulk of the thin-source bremsstrahlung will be produced in a narrow shell near the photosphere.

From equation (12) we see that the photospheric temperature required to reradiate the absorbed x-ray energy will be $3.3 \times 10^5$ $^{o}$K.

The spectrum will therefore be peaked near the 44-60 angstrom band in which Byram, Chubb, and Friedman[11] have observed an additional component of x-radiation from the Scorpius source. Their estimate of the interstellar opacity at 44 angstroms is based on an assumed H/He ratio of 7, but we prefer to assume double this number, which would be more characteristic of solar abundances. At an assumed distance of 200 parsecs, and with an interstellar gas density of one H atom per cubic centimeter, 44 angstrom radiation is attenuated by one order of magnitude. Hence, in the absence of attenuation, Byram et al should have seen about $10^{-6}$ erg/cm.$^{2}$sec. in the 44-60 angstrom band, corresponding to a luminosity of $\sim 4\mathrm{x}10^{36}$ erg/sec. in this band from the Scorpius source. This is an order of magnitude higher than the above discussion of our model would indicate.

However, we do not believe that this is necessarily a difficulty with our model. We have seen that there is a rapid transfer of mass through the photosphere. If the total luminosity of the Scorpius source corresponds to the radiation stress limit, with much of the gravitational energy release occurring inside the photosphere, then the photospheric luminosity could be higher than the x-ray luminosity by a substantial factor. The white dwarf mass could also be substantially higher than 0.2 solar masses.

It is unlikely that the rapid rate of mass transfer to the white dwarf star can continue for a very long period without producing significant effects in the white dwarf itself. When a thick hydrogen-rich surface layer has been added, the hydrogen-burning shell source will be activated, and there may be an instability which will lead to nova explosions which will prevent the total mass from increasing too rapidly.

Since the binary companion will fill its Lagrangian surface in order to carry out rapid mass transfer, it will subtend to solid angle at the white dwarf $\sim \pi$. Hence $\sim 1/4$ of the white dwarf luminosity will be absorbed and reradiated by the companion. There will be a large variation in the radiating temperature, but its general range will be of the order $T \sim (L/4\pi R_c^2 \sigma)^{\frac{1}{4}}$, where $R_c$ is the radius of the companion. If we take $L \sim 8\text{x}10^{37}$ erg/sec. and $R_c \sim 2\text{x}10^{11}$ cm., then $T \sim 4\text{x}10^4$ $^oK$.

The thin-source bremsstrahlung radiation will have a low-energy tail which will make a substantial contribution to the optical emission, as observed. The reradiation by the white dwarf is peaked at a sufficiently high energy that there will be no substantial contribution in the visible. On the other hand, the reradiation by the companion is peaked at a sufficently low temperature that a substantial visible contribution is likely. We would therefore expect a variable visible luminosity, with a regular component due to orbital motion and an irregular component due to variable gas streams between the stars. The emission lines could well vary with respect to the continuum in this model.

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